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Identifying an SM-like Higgs particle at future colliders

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Abstract

It is possible that at the Tevatron, LHC and e^+e^- Linear Collider only one light Higgs boson will be found, with properties (basic couplings to W/Z and to fundamental fermions, mass, CP property) as expected in the Standard Model. This, SM-like scenario can be realized in a Two-Higgs-Doublet Model both with and without decoupling. Precise measurements of the Higgs boson coupling to gluons at the LHC and to photons at a Photon Collider allow to distinguish between the SM and various realizations of a SM-like scenario.

SM-like scenario. One of the great challenges at future colliders will be the SM-like scenario that no new particle will be discovered at the Tevatron, the LHC and electron-positron Linear Collider (LC) except the Higgs boson with partial decay widths, for the basic channels to fundamental fermions (up- and down-type) and vector bosons W/Z, as in the SM:

$$\left|\frac{\Gamma_i^{\rm exp}}{\Gamma_i^{\rm SM}}-1\right| = \left|\left(\frac{g_i}{g_i^{\rm SM}}\right)^2-1\right| \lesssim \delta_i \ll 1, \text{ where } i=u,d,V. \tag{1}$$

New physics may still be seen via deviations of some observables from the SM predictions. The Higgs-boson loop couplings with photons or gluons are very promising for such studies. In the SM and in its extensions, all fundamental charged particles, with mass arising from a Higgs mechanism, contribute to the Higgs boson effective couplings with photons, and, similarly, all quarks contribute to the Higgs boson coupling to gluons. These couplings are absent in the SM at tree level, and therefore, the relevant background will be relatively low.

Results from the LHC and LC can be combined and thus facilitate in distinguishing models. We stress here in particular the role of the $\gamma\gamma$ mode of a linear collider (Photon Collider), where the expected accuracy of the measurement of the two-photon width for Higgs mass equal to 120 GeV is of the order of 2% [1] in comparison to the LHC and LC with the corresponding accuracy 15–20% [2, 3].

Here we assume that one neutral Higgs particle has been found at the LHC with all basic couplings, within the experimental accuracy, as expected in the SM. So, we have for relative couplings:

$$\chi_i=\frac{g_i}{g_i^{\rm SM}}, \quad \text{with } \chi_i^{\rm obs}=\pm(1-\epsilon_i), \quad \text{and } |\epsilon_i|\le\delta_i \quad \text{for } i=u,d,V. \tag{2}$$

Additional constraints on these ϵ_i follow from the considered model.

We consider the Two-Higgs-Doublet Model (2HDM) with no or weak CP-violation, using the soft Z_2-violation potential as given by [4–7]. We introduce a parameter μ via the real part of the coefficient of the bilinear mixing term $\mathrm{Re}\,(m_{12}^2) = 2\mu^2 v_1 v_2/v^2$ [7]. For $\mu^2 \gg |\lambda_i| v^2$ the SM-like scenario with decoupling is realized. The SM-like scenario can also be realized for $\mu < v$ with non-decoupling, in particular for $M_{H\pm} \approx M_H \approx 700$ GeV, $M_A \approx 600$ GeV and M_h=120 GeV, $\mu < 0.3\, M_{H\pm}$, with λ_i within perturbativity and even unitarity constraints. The Yukawa interactions are of Type II with the basic couplings constrained by $(\chi_u + \chi_d)\chi_V = 1 + \chi_u \chi_d$ (pattern relation [7]), valid for each neutral Higgs boson, even in the general CP-violating case.

The SM-like scenario corresponds to the observation of either h or H. We distinguish solutions A and B (see ref. [7] and table 1) for the realization of an SM-like scenario for the observed Higgs particle with mass 110 to 250 GeV. In solutions A all basic (relative) couplings are close to 1 or all are close to -1. Note that only solution A_{h+} is realized in the decoupling limit. In solutions B, one basic coupling, χ_u or χ_d, has opposite sign to the other two, and obviously one expects here larger deviations from the SM than for solutions A. One can see that the decay width $h(H)Z\gamma$ is less sensitive to the discussed effects of 2HDM than the $h(H)\gamma\gamma$ one.[1]

solution	basic couplings	$\lvert\chi_{gg}\rvert^2$	$\lvert\chi_{\gamma\gamma}\rvert^2$	$\lvert\chi_{Z\gamma}\rvert^2$
$A_{h\pm}/A_{H_-}$	$\chi_V \approx \chi_d \approx \chi_u \approx \pm 1$	1.00	0.90	0.96
$B_{h\pm d}/B_{H-d}$	$\chi_V \approx -\chi_d \approx \chi_u \approx \pm 1$	1.28	0.87	0.96
$B_{h\pm u}$	$\chi_V \approx \chi_d \approx -\chi_u \approx \pm 1$	1.28	2.28	1.21

Table 1: *SM-like realizations in the 2HDM II [7], together with ratios of partial widths to their SM values for $M_{h(H)} \approx 120$ GeV for the case $|\chi_i| = 1$, $M_{H^\pm}$ =700 GeV and $\mu \lesssim 0.3 M_{H^\pm}$.*

The two-gluon decay width. The two-gluon width will be measured at the LHC. This quantity is for solutions A practically equal to the SM prediction (see table 1).

In the SM the contributions of t and b quarks partly cancel, while for solutions B they add, giving larger deviations from the SM predictions. In Fig. 1 (left) the solid curve corresponds to the case $\chi_u = -\chi_d = \pm 1$ for all solutions B. The shaded bands reflecting $1\ \sigma$ experimental uncertainties correspond to the B_{h+u} case only.

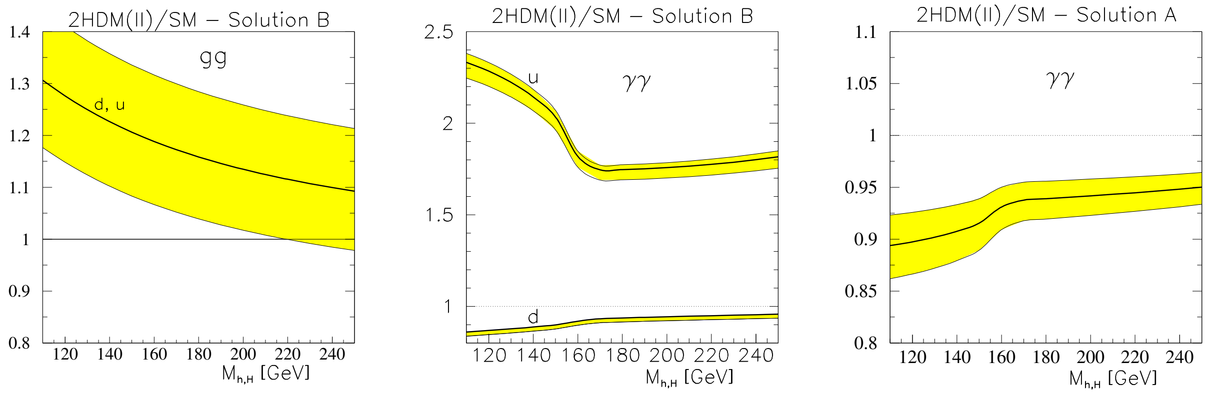

Figure 1: *Ratios of the Higgs boson decay widths in the SM-like 2HDM II and the SM as functions of $M_{h,H}$ for solutions B and A for $M_{H^\pm}$=700 GeV and $\mu \lesssim 0.3 M_H^\pm$.*

[1]The process $e\gamma \to eh(H)$ with large transverse momentum of the scattered electron, has a sensitivity from the $h(H)Z\gamma$ vertex, with Z far from the mass shell, similar to that of $h(H) \to \gamma\gamma$ [8].

The two-photon decay width. For solutions A the widths $h(H) \to \gamma\gamma$ and $h(H) \to Z\gamma$ will differ from the SM predictions due to the charged Higgs boson contribution, proportional to the trilinear coupling hH^+H^- (HH^+H^-), so we have:

$$\chi_{H^\pm} \equiv -\frac{v g_{hH^+H^-}}{2M_{H^\pm}^2} = \left(1 - \frac{M_h^2}{2M_{H^\pm}^2}\right)\chi_V + \frac{M_h^2 - \mu^2}{2M_{H^\pm}^2}(\chi_u + \chi_d), \tag{3}$$

and similarly for H. The value of $\chi_{H^\pm}$ is close to $\chi_V \approx \pm 1$ (non-decoupling) at the considered small values of $(M_h^2/2M_{H^\pm}^2)$ for solutions A and $(\mu^2/M_{H^\pm}^2)$ for solutions B.

For solutions $B_{h\pm d}$ the main deviation from that of the SM is like for solution A given by the contribution of $H^\pm$. For the solution B_{h+u} the effect of the change of sign of the coupling $ht\bar{t}$ dominates.

The ratios of the two-photon Higgs widths to the SM value are shown in Fig. 1 (see also table 1) for solutions B (center) and A (right). The results are presented without (solid lines) and with realistic 1 σ uncertainties (shaded bands) around the SM values of the measured basic couplings [3].

Conclusion. We analyse, using realistic estimates of experimental uncertainties, the potential of future colliders to determine the nature of an SM-like Higgs boson, SM or 2HDM, for mass 110–250 GeV. It is crucial to combine precise measurements of loop couplings involving gluons at LHC and photons and photons at a Photon Collider, as only couplings to photons are sensitive to the decoupling property of the model.

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